A wood and fibre quality-deterioration model for mountain pine beetle-killed trees by biogeoclimatic subzone

Tennessee Trent, Val Lawrence, Kathy Woo

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Abstract

Thirty-nine sample sites were established across the Sub-Boreal Spruce and Sub-Boreal Pine–Spruce biogeoclimatic zones, in order to conduct a preliminary wood-quality–based assessment of the shelf life of mountain pine beetle-killed lodgepole pine. A Biogeoclimatic Ecosystem Classification was completed at each site and wood cores were collected from 10 trees. Cores were used to determine average fibre length and fibre coarseness by fibre-quality analysis, and wood density, tracheid (fibre) diameter, cell-wall thickness, fibre coarseness, microfibril angle (MFA), and stiffness (modulus of elasticity; MOE) by SilviScan analyses. Wood extractive contents were measured gravimetrically. Decay content was measured on 291 cores, using a near-infrared method to predict caustic solubility. Moisture content was measured for 69 cores representing 28 sites. All results were compared against time-since-death estimates derived from overview flight data provided by various forest management professionals.

These preliminary assessments suggest that variation in wood and fibre properties, with the exception of moisture content, could not be explained as a function of time since death. However, an exact determination of kill date proved very challenging and may affect these data. While the shelf life of mountain pine beetle lodgepole pine for the sample area may be greater than 5 years, the decreasing moisture content of dead pine adds challenges for industrial use that cannot be explained by the analyses above. Further discussion explores the potential of natural disturbance as a more influential factor in determining shelf life than any intrinsic wood properties. Correlations between measures of potential site productivity and length weighted fibre length are demonstrated and discussed.

Keywords: Mountain pine beetle, shelf life, biogeoclimatic ecosystem classification, SilviScan, fibre-quality analysis, decay, moisture content

Résumé

Afin de mener une évaluation préliminaire de la qualité du bois pour déterminer la durée de conservation des pins tordus tués par le dendroctone du pin ponderosa, trente-neuf sites d'échantillonnage ont été établis dans les zones biogéoclimatiques subboréales d'épinettes ainsi que de pins et épinettes. Chaque site a été évalué à l'aide du Système de classification biogéoclimatique des écosystèmes (SCBG), et des carottes ont été extraites de 10 arbres. Les carottes ont permis de déterminer la longueur et la grossièreté moyennes des fibres grâce à l'analyse de la qualité de la fibre et de la densité du bois, le diamètre des trachéides (fibres), l'épaisseur des parois cellulaires, la grossièreté des fibres, l'angle des microfibrilles et la rigidité (module d'élasticité) au moyen des analyses Silviscan. On a mesuré la teneur en produits d'extraction du bois à l'aide d'une analyse gravimétrique. On a mesuré le taux de pourrissement dans 291 carottes en utilisant la technologie du proche infrarouge (NIR) afin de prédire la solubilité avec des substances caustiques. La teneur en eau a été mesurée à partir de 69 carottes en provenance de 28 sites différents. On a comparé tous les résultats avec les estimations du temps écoulé depuis la mort des arbres obtenues à partir de données aériennes fournies par divers professionnels de l'aménagement forestier.

Ces évaluations préliminaires indiquent que la variation des propriétés du bois et de la fibre, à l'exception de la teneur en eau, ne peut être expliquée en fonction du temps écoulé depuis la mort des arbres. Toutefois, il a été très difficile de déterminer la date exacte de la mort, ce qui pourrait avoir une incidence sur les données. Bien que la durée de conservation du bois issu des pins tordus tués par le dendroctone du pin ponderosa dans les zones d'échantillonnage puisse être plus longue que cinq ans, la diminution de la teneur en eau des pins morts rend difficile leur utilisation industrielle, ce qui ne peut être expliqué à l'aide des analyses mentionnées précédemment. Une autre étude se penche sur la possibilité que les perturbations naturelles

soient un facteur plus déterminant, en ce qui a trait à la durée de conservation, que n'importe quelle propriété intrinsèque du bois. Cette étude aborde et montre les corrélations qui existent entre les données sur la productivité potentielle des sites et la mesure pondérée de la longueur de la fibre.

Mots-clés : Dendroctone du pin ponderosa, durée de conservation, système de classification biogéoclimatique des écosystèmes, Silviscan, analyse de la qualité de la fibre, pourrissement, teneur en eau

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Introduction

British Columbia has an estimated 10 million hectares of lodgepole pine forest (*Pinus contorta* Dougl. Ex Loud. var. *latifolia Engelm.*). The current outbreak of mountain pine beetle (*Dendroctonus ponderosae* Hopkins) is estimated to have affected more than 8.7 million hectares as of 2005 (BCMoF 2006).

Annual allowable cut has been increased in beetle-affected areas. This increase is predicted to be followed by a 15% to 29% decrease in pre-uplift harvest levels. In addition, an estimated 200 million m^3 of mountain pine beetle-killed lodgepole pine is projected to remain unharvested after the outbreak subsides (BCMoF 2003). The threat to timber resources in British Columbia—and to the industries that use these resources—is illustrated by these numbers.

One of the central concerns about beetle-killed trees in British Columbia is their shelf life. Questions remain as to how long standing dead lodgepole pine will remain industrially useful. Definition of shelf life must consider the end product to be manufactured from the resource. Hence, rapid assessment methods that can determine quality of wood in stands are critical to longer-term determination of end-use applicability. If wood-quality attributes can be linked to kill date and site quality, this would enable forest managers to plan harvesting schedules in accordance wit wood-quality deterioration rates.

In this preliminary study, we endeavoured to define the most appropriate wood-quality attributes by kill date across a wide range of site conditions using state-of-the-art rapid wood-quality assessment tools that are available through the EvaluTree™ unit of PAPRICAN. It must be emphasized that given the extent of the epidemic, the range of site quality affected, and the relatively short duration of the epidemic to date, the sampling challenges associated with this preliminary trial were significant.

Material and methods

Field sampling

Field sampling for this project was completed between September 08, 2004, and December 14, 2005. A total of 39 sample plots were established in mature mountain pine beetle-infested lodgepole pine-dominated stands (Figure 1).

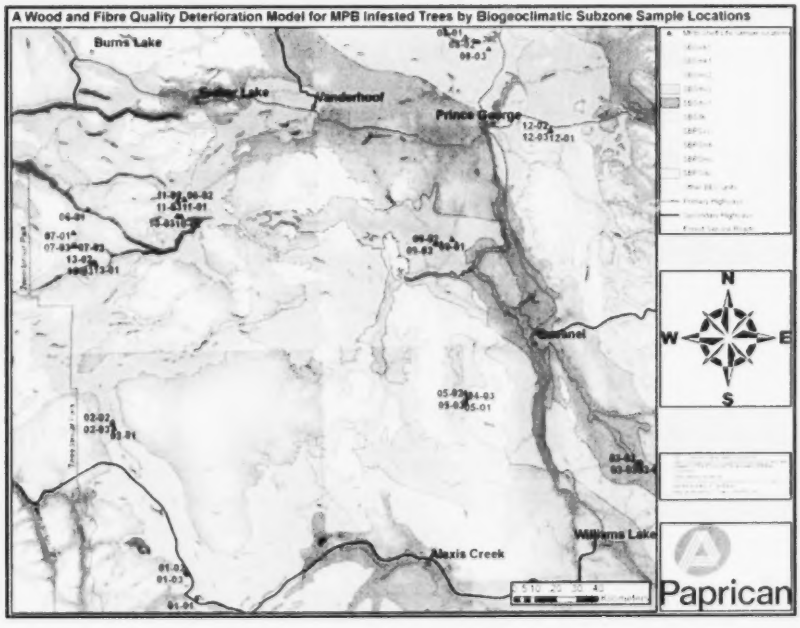

Figure 1. A map of sample locations, biogeoclimatic subzones, and major geographic features in central British Columbia.

Sample criteria included sampling in the Sub-Boreal Spruce (SBS) and Sub-Boreal Pine–Spruce (SBPS) biogeoclimatic zones (Meidinger and Pojar 1991). Within each zone a variety of biogeoclimatic sub-zones were targeted. Potential sample sites were located with the aid of local licensees and British Columbia Ministry of Forests personnel. Biogeoclimatic ecological classification (BEC) maps and detailed mountain pine beetle-attack history data (in the form of overview flight data) were consulted to establish potential sampling sites. Practical considerations involved road access and land tenure.

Once located on maps, potential sample sites were field checked. Intact beetle-infested stands in a variety of site series within each subzone were targeted (Banner et al. 1993; DeLong 2003; Steen and Coupé 1997). In addition, a range of time-since-death classes were targeted. These two criteria were, at times, conflicting, and some deviation of the original sample plan was required. If all considerations were met at a potential site, a sample plot was established.

Establishing a sample plot involved a preliminary assessment of the site series of the given sub-zone. A site deemed to be representative of the target site series was then chosen as the plot centre. The plot centre location was marked with a stake and global positioning system co-ordinates were recorded (GPS co-ordinates were recorded in decimal degrees using the WGS_84 datum; Snyder 1987). Once the sample site was chosen and marked, all measurements and samples were collected.

Measurements at each plot included Biogeoclimatic ecological classification-unit determination (which includes determination of soil moisture and nutrient regimes, measurement of site data, and shrub, herb and graminoid vegetation attributes), sample-tree measurements (height and diameter) and increment coring. Two 10-mm increment cores were taken from each of 10 sample trees at each site (excluding site 13, at which two 12-mm increment cores were taken from each stem. Site 13 was sampled late in 2005, and increment borers of 10-mm diameter were no longer available.) Access notes were taken to complement the GPS co-ordinates.

Kill-date determination

Kill dates for sample sites were determined using two methods. The first method, used at all sample locations except sites 01-01, 01-02, 01-03, 02-01, 02-02, 02-03, 03-01, 03-02 and 03-03, used overview flight data provided by local forest management professionals. Areas of red-attack stands were identified from historical overview flight maps in target BEC subzones and were then field checked. Red attack indicates a successful mountain pine beetle attack in the previous growing season, and allowed for a reasonable estimation of kill dates at these sites.

At sites 02 and 03, tree characteristics were used to estimate kill date. Data were recorded on colour and percentage of remaining foliage, condition and extent of remaining bark, and number of remaining branches. These data were then considered against criteria listed in Table 1.

Table 1. Tree characteristics used to determine time since death at sites 02-xx and 03-xx. (adapted from Thrower et al. 2005).

Years since death	Characteristics
1	Red attack: no needle loss
2–4	Red attack: some to almost all needles lost
5–7	Grey attack: all needles lost; some small branches lost
8+	Grey attack: all small branches lost

Kill-date determination at site 01 involved attempts at correlating ring-width patterns from sample trees with master chronologies created in an unrelated study by researchers at the Pacific Forestry Centre (David Lewis 2004, unpublished). These correlations proved unreliable. However, reasonable estimation of kill date for these sites was determined using a combination of factors including stage of attack (i.e., advanced grey stage) and beetle-attack histories from the region (Shore 2001, unpublished).

Fibre-quality analysis

Fibre-quality analysis was conducted on increment cores collected from the field. Annual growth rings were counted on cores and then three age classes were cut out for fibre-quality analysis. These age classes represented mature wood sections from each stem and were from ranges of 40 to 60 years, 60 to 80 years, and 80 to 120 years.

Each section was first cooked in water for four hours at 120 °C. Following this, each age class was macerated in a solution of equal parts hydrogen peroxide and glacial acetic acid for 48 hours at 70 °C. The resulting pulp was dispersed using a Hamilton Beach mixer and diluted to a target consistency. Each sample was analyzed in duplicate on the Fibre Quality Analyzer (FQA) to determine length weighted fibre length (LWFL) and fibre coarseness.

SilviScan analysis

The Marcus Wallenberg prize-winning SilviScan system (developed by the Commonwealth Scientific and Industrial Research Organization [CSIRO] Forestry and Forest Products Division) is a suite of instruments designed for rapid and non-destructive assessment of wood and fibre properties of solid wood (Lawrence and Woo 2005).

The current version is SilviScan 3 (SS3). This consists of three analytical units: a cell analyzer, a densitometer, and a diffractometer. SilviScan uses a range of analytical technologies, including optical microscopy, X-ray diffractometry, X-ray densitometry, image analysis, and applied mathematics, to determine many wood-fibre properties that govern product quality. These properties include fibre diameter, fibre-wall thickness, wood density, coarseness, microfibril angle (MFA), and wood stiffness (modulus of elasticity, or MOE).

In contrast to conventional densitometry and diffractometry methods, SilviScan's technology integrates growth-ring orientation information and automated sample-stage rotation. This provides precise and distinct densitometric and diffraction measurements from early-wood and late-wood fibres within a sample, resulting in sharp definition of growth-ring boundaries.

Sample Preparation

The cores were ethanol-dehydrated directly upon receipt to prevent fungal growth and minimize fibre collapse and internal checking. After air-drying, the cores were debarked, and shipped to CSIRO, in Australia, for additional preparation and analysis. At CSIRO, the cores were further processed, using high-accuracy twin-blade saws to produce wood strips that were 2 mm wide, 7 mm high, and oriented pith to bark; subsequent measurements were obtained from these strips. The strips were resin-extracted overnight with hot acetone to eliminate contribution of resin in subsequent density measurements. The cross-sectional plane of each wood strip was sanded and polished using a custom-built pneumatic sanding system. The wood strips were then stored under the same controlled temperature and relative humidity conditions (20 °C, 40% relative humidity) under which they were analyzed.

Cell Analyzer

The polished cross-sectional plane of each wood strip was scanned for cell-size, -type, and -distribution information using an optical microscope equipped with a high-resolution video camera. Sample length was measured by locating the bark and pith ends of a sample in the microscope frame. Images and positional information were recorded during the scan; post-scan analysis was performed to extract property profiles from the succession of images onto a standardized distance scale along the sample axis.

Each successive image was binarized and processed to identify radial and tangential cell-wall boundaries. Further image analysis was performed to determine average radial and tangential fibre diameters, and to estimate tracheid perimeters and cell population within a 50-µm radial interval to match the density measurements obtained by X-ray densitometry. As each sample was 2 mm wide, each 50-µm interval represents approximately 50 to 100 tracheid cross sections.

Image analysis was also used to estimate growth-ring orientation relative to the radial side of the wood strip. This information was then accessed by the densitometric and diffraction programs to position the wood strip using SS3's goniometric stage, so that the growth rings remained parallel to the X-ray beam during subsequent data acquisition.

Densitometer

The average conditioned density (20°C; 40% relative humidity) of each sample was first determined gravimetrically from its volume (micrometry) and weight, and was used to normalize subsequent density profiles obtained through X-ray densitometry. An X-ray beam was passed through the wood sample perpendicular to the radial–longitudinal surface, and density measurements were recorded every 50µm. Growth-ring orientation information obtained from the cell scanner was used to rotate the sample, using SilviScan's goniometric stage, so that the rings remained parallel to the X-ray beam throughout the scan. This increased accuracy of the densitometry measurements by allowing sharper definition of density-contrast edges in the sample.

X-ray absorbance was related to density, according to Beer's Law. Resulting data points were tabulated in pith-to-bark radial profiles along the sample length, where position 0 is the pith end. Density and fibre-diameter information (obtained from the cell scanner) were combined to calculate fibre-wall thickness, coarseness, and specific surface area.

All density measurements provided for this project were decreased by 20% to obtain corresponding basic density values (oven-dry mass/green volume).

Diffractometer

An X-ray beam was passed through the wood sample perpendicular to the radial–longitudinal surface; the resulting diffraction patterns were recorded using a two-dimensional wide-angle X-ray detector. Growth-ring orientation information obtained from the cell scanner was used to rotate the sampl,e using SilviScan's goniometric stage, so that the rings remained parallel to the X-ray beam throughout the scan.

Diffraction patterns produced from the wood enabled determination of microfibril angle (MFA) of the fibres. SilviScan uses the relationship between variance of the cellulose-I 002 azimuthal diffraction patterns and microfibril angle dispersion to estimate MFA. MFA profiles were generated at a 5-mm radial step size.

SilviScan modulus of elasticity (MOE) estimates were derived from a combination of densitometric and diffractometric information, based on a model that includes the density measurements and X-ray diffraction-profile intensity variations.

Post Data Analysis

In addition to the raw data profiles, wood and fibre properties were also provided as both unweighted and area-weighted core averages, where the area weighting emphasized contributions from the outer rings of the tree. Weighting by radius is similar to weighting by the length of the perimeter corresponding to the point where the property is measured.

Extractives

Total extractive content was obtained using a modified version of the Technical Association of the Pulp and Paper Industry method T280 pm-99 (TAPPI 2002). The core samples were placed into Soxhlet thimbles and extracted using a Soxhlet extraction apparatus for 6 hours with 200 mL of acetone, after which the acetone extracts were concentrated with a rotary evaporator down to approximately 10 mL. The extracts were then passed through a Pasteur pipette that was packed

with glass wool to filter out solid-wood impurities into a pre-tared scintillation vial. Further concentration of the extract residue was performed by passing a stream of nitrogen gas into the vial while it was being warmed, resulting in 1 mL of residue. This was freeze-dried to eliminate remaining moisture, and weighed to obtain the total content of extractives present in the core sample.

Decay extent and moisture content

Decay

Decay extent on a subsample of cores was measured using a 1% caustic solubility method. This method was adapted from the Pulp and Paper Technical Association of Canada Standards G.6 and G.7 (CPPA 2003) and TAPPI Standard T212 om-98 (TAPPI 2002). Adaptations to these procedures were made to process very small sections (1 cm) of increment cores as validation for a near-infrared tool in development at Paprican (MPBI #8.14).

The test involves adding sodium hydroxide (NaOH) to milled wood in order to separate soluble and insoluble wood components. These two components are then physically separated using filter paper; acid is used to neutralize the filtrate. The filter (which now contains the insoluble wood) is oven dried to evaporate water. With the insoluble wood separated, the percentage of insoluble wood compared to the entire wood sample is calculated. This percentage is the caustic solubility, and indicates decay content, with higher percentages equating to a higher levels of decay.

A spectroscopic partial least squares (PLS1) model to predict decay content was developed using chemometric analysis. This work was done as part of PAPRICAN's MPBI 8.14 project to develop a field sensor to measure various indicators of wood quality in beetle-attacked trees. The decay model was built on spectroscopic data (350 nm to 2500 nm) collected at 1-cm increments on tree cores, using the TAPPI standard 1% caustic solubility as a reference method. Twenty cores were used to build the model, representing 20 of the 36 sample sites. Decay predictions were done at 1-cm increments for 291 of the original 360 cores. The decay values at 1-cm resolution were averaged to give an average decay value for each tree. The root-mean-square error of prediction for the site-averaged, predicted decay values was calculated to be 5.1%, with respect to using the TAPPI-measured lab values (at 1-cm resolution) to determine the site-average decay content.

Moisture content

Moisture content was measured on 69 cores that represented 28 sites. Green and oven-dried mass was measured for each core. These numbers were then converted to percentages and expressed as percent moisture of the oven-dried wood. The general formula for calculating moisture content on an oven-dried basis is given below.

$$MC = [1 - (o.d\ mass/green\ mass)] * 100$$

Checking studies: image analysis of disks

Images of the discs were captured using an Olympus Camedia D-545 digital camera mounted on a Nikon Multiphot macro stand. A 30-cm ruler was photographed under the same conditions to provide a scale for calibrating the images.

Images were saved as TIFF files. The files were processed in Adobe Photoshop 7.0 to prepare them for image analysis. From each original disc image, two images for analysis were prepared: one showing only wood (no bark); one only checks. An example is shown in Figure 2.

Images were analyzed in Image Pro Plus 4.5. Total area and average diameter were measured for the disc images. For the check images, individual check area and length were measured. Measurements from Image Pro were exported to Excel. The image of the ruler was analyzed to obtain the calibration value for the images. Pixel-based measurements from Image Pro were converted to measurements in millimetres using the calibration value.

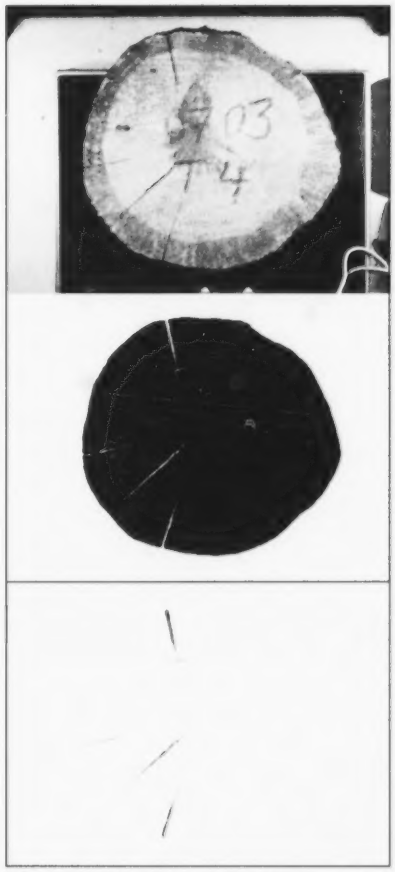

Figure 2. Disc T4. Top to bottom: original image; image processed to show only wood; image processed to show only checks.

Results and discussion

Field sampling

In total, four subzones were sampled from the Sub-Boreal Pine–Spruce biogeoclimatic zone (SBPS) and six from the Sub-Boreal Spruce biogeoclimatic zone (SBS). Within the subzones of the SBPS, 11 site series were sampled. Twelve discrete site series were sampled from the SBS subzones.

Site index (SI)—a measure of potential site productivity measured in tree height at 50 years breast height age—was determined using the site index for biogeoclimatic ecosystem classification (SIBEC) method (BCMoF 1997). These values were used to compare sites across the variety of climatic conditions sampled.

Kill-date determination

Overview flight data provided by local forest management professionals were used for the majority of sample sites. This proved to be the most reliable method to estimate kill dates used in this study.

Dendrochronological estimations of kill date at site 01 proved unreliable. However, historical data for the Chilcotin Plateau region indicate that a significant mountain pine beetle outbreak occurred throughout the 1980s and ended in the late 1980s (peak = 1989) (Shore 2001, unpublished data). Successful dendrochronological kill-date determination conducted in the immediate vicinity of site 01-01 indicates beetle-induced mortality dates of 1976 and 1977. These factors combined with the advanced grey-stage appearance of the PAPRICAN sample trees indicate that trees representing sites 01-01, 01-02

Table 2. Biogeoclimatic Ecosystem Classification (BEC) zone and subzone variant, site series, and site index for sample sites.

Site	BEC Subzone (variant)	Site Series	Pli Site Index (m) (SIBEC)
01-01	SBPSxc	01	15
01-02	SBPSxc	02	12
01-03	SBPSxc	05	15
02-01	SBPSmc	01	12
02-02	SBPSmc	04	9
02-03	SBPSmc	05	15
03-01	SBSdw1	01	24
03-02	SBSdw1	01	24
03-03	SBSdw1	01	24
04-01	SBPSmk	04	18
04-02	SBPSmk	06	21
04-03	SBPSmk	01	18
05-01	SBPSdc	01	18
05-02	SBPSdc	05	15
05-03	SBPSdc	01	18
06-01	SBSdk	03	15
06-02	SBSdk	03	15
06-03	SBSdk	01	18
07-01	SBSmc2	01	18
07-02	SBSmc2	05	21
07-03	SBSmc2	02	15
08-01	SBSmk1	04	21
08-02	SBSmk1	09	21
08-03	SBSmk1	04	21
09-01	SBSdw2	07	18
09-02	SBSdw2	01	21
09-03	SBSdw2	01	21
10-01	SBSdk	03	15
10-02	SBSdk	03	15
10-03	SBSdk	03	15
11-01	SBSdk	03	15
11-02	SBSdk	03	15
11-03	SBSdk	03	15
12-01	SBSwk1	05	21
12-02	SBSwk1	05	21
12-03	SBSwk1	06	21
13-01	SBSdk	01	18
13-02	SBSdk	01	18
13-03	SBSdk	01	18

and 01-03 were killed some time in the mid to late 1980s. Although not supported by the above mentioned dendrochronological methods, the assumption that these trees were killed by 1989 (end of the Chilcotin outbreak) seems reasonable and is used in this paper. Kill date was determined for sites 02 (02-01, 02-02, 02-03) and 03 (03-01, 03-02, 03-03) using foliar, branch and bark indicators as mentioned above.

Table 3 summarizes kill-date estimates by site and estimation method. A frequency table of site and kill date is shown in Table 4.

Table 3. Kill date, time since death and the kill-date estimate method for sample sites.

Site	Kill Date	Time Since Death in 2004 (years)	Estimation Method
01-01	1989	15	Deduction
01-02	1989	15	Deduction
01-03	1989	15	Deduction
02-01	2002	2	Foliar indications
02-02	2002	2	Foliar indications
02-03	2002	2	Foliar indications
03-01	1999	5	Foliar indications
03-02	2000	4	Foliar indications
03-03	2000	4	Foliar indications
04-01	1999	5	Overview flight
04-02	2000	4	Overview flight
04-03	2001	3	Overview flight
05-01	2000	4	Overview flight
05-02	2000	4	Overview flight
05-03	2000	4	Overview flight
06-01	1999	5	Overview flight
06-02	1999	5	Overview flight
06-03	1999	5	Overview flight
07-01	1996	8	Overview flight
07-02	1996	8	Overview flight
07-03	1996	8	Overview flight
08-01	2001	3	Overview flight
08-02	2001	3	Overview flight
08-03	2001	3	Overview flight
09-01	2002	2	Overview flight
09-02	2002	2	Overview flight
09-03	2002	2	Overview flight
10-01	1999	5	Overview flight
10-02	1999	5	Overview flight
10-03	1999	5	Overview flight
11-01	1999	5	Overview flight
11-02	1999	5	Overview flight
11-03	1999	5	Overview flight
12-01	2002	2	Overview flight
12-02	2002	2	Overview flight
12-03	2002	2	Overview flight
13-01	1996	8	Overview flight
13-02	1996	8	Overview flight
13-03	1996	8	Overview flight

Table 4. Frequency distribution of kill date by site.

Time since death (years)	Number of sample sites represented	Percentage of total sample sites represented
2	9	23
3	4	10
4	6	15
5	11	28
8	6	15
15	3	8

Fibre-quality analysis

A total of 338 cores were analyzed using the fibre-quality analysis. Depending on the age of a tree, as many as three age classes from each core were analyzed, for a total of 891 samples run in duplicate. The resulting data show no apparent correlation between length weighted fibre length (LWFL) and time since death, as expected (Figure 3).

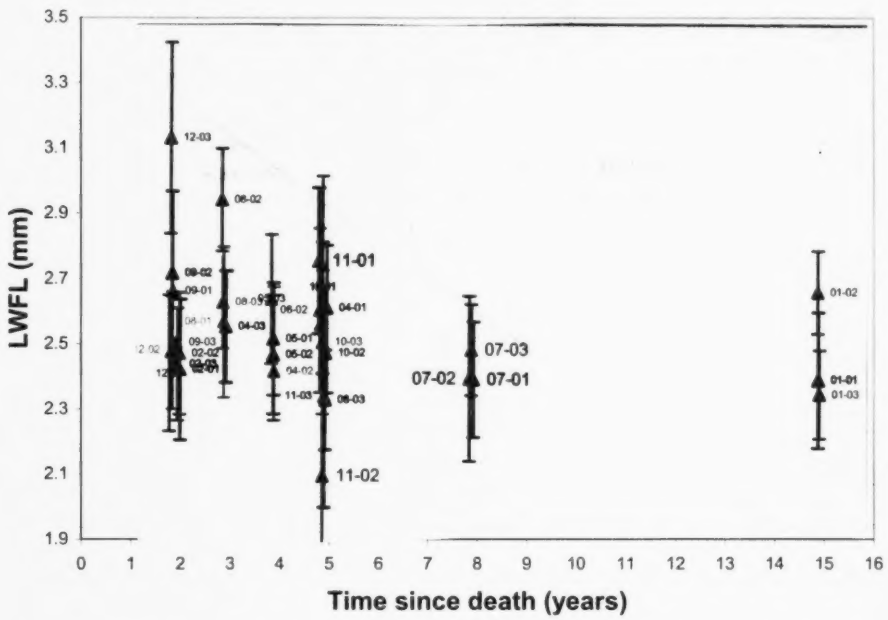

Figure 3. Average length-weighted fibre length versus time since death for sites across the 60- to 80-year age class. Error bars represent 1 standard deviation at a 95% confidence interval.

The range given in Figure 3 (approximately 2.1 mm to 3.1 mm) is normal for lodgepole pine in sub-boreal climates, and likely represents a range of natural variation (Pitts et al. 2001). This is essentially a measure of the length of the tracheid. Because all of these values fit into a normal distribution for live trees, we can assume that the tracheid cell wall is intact. These data indicate that LWFL is not affected by beetle-induced tree death for up to 15 years after mortality. The variation noted above may be partially explained through site index.

Figure 4 displays a linear relationship between LWFL and site index. Such relationships have been displayed in the past and explain some variation in fibre-length measures from across the sample area (Pitts et al. 2001). LWFL and site index values in Figure 4 are averaged for each sample area (i.e., results from sites 01-01, 01-02 and 01-03 have been averaged for both LWFL and site index); therefore, each measure represents a biogeoclimatic subzone (see Table 2). Because biogeoclimatic subzone is recognized to be representative of the regional macroclimate, this figure essentially illustrates a link between LWFL and climate (Meidinger and Pojar 1991). Other factors that may influence LWFL, such as tree genetics, inter-specific competition and ecological associations (e.g., tree–mycorrhizal associations), are not considered here.

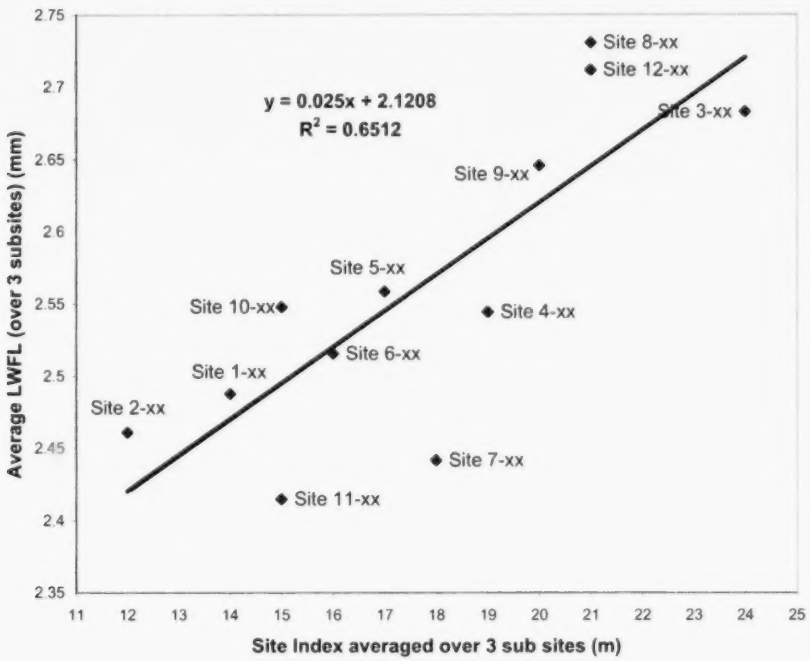

Figure 4. Average length weighted fibre length (LWFL) vs average site index for 12 sites representing a positive linear relationship between LWFL and average site index for biogeoclimatic subzone (regional macroclimate).

Coarseness is a measure of tracheid mass per unit length (normally expressed as grams per meter). Significant reductions in coarseness across a time-since-death continuum may indicate cell-wall deterioration due to decay. No such relationship was noted (Figure 5).

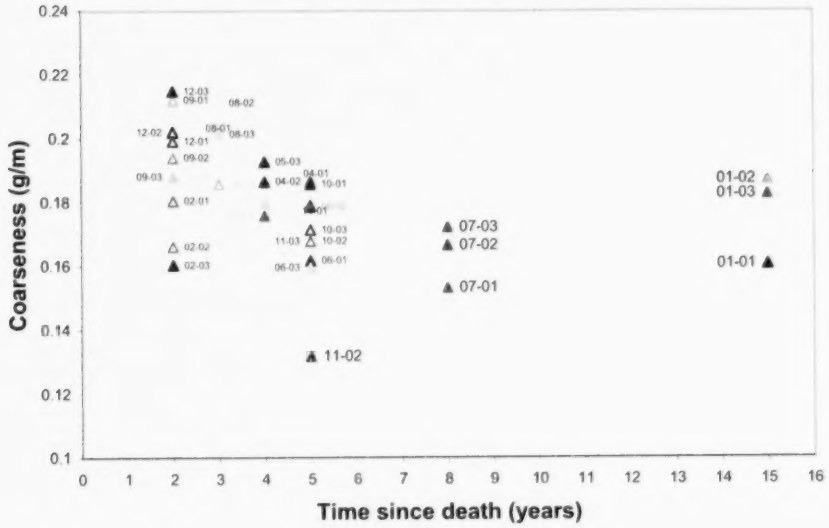

Figure 5. Coarseness versus time since death for all sites.

Coarseness values shown in Figure 5 fit a normal distribution for lodgepole pine grown in sub-boreal climates (Pitts et al. 2001). The relative stability of these values indicates that there is no significant decay in the cell walls of tracheids measured for this study. Fibre coarseness and LWFL are related; associations can be made between those two properties and site index (Pitts et al. 2001).

Figure 6 shows the positive, linear relationship between the fibre properties of LWFL and coarseness. Although the correlation is poor (R^2 = 0.36), this trend has been demonstrated (Pitts et al. 2001).

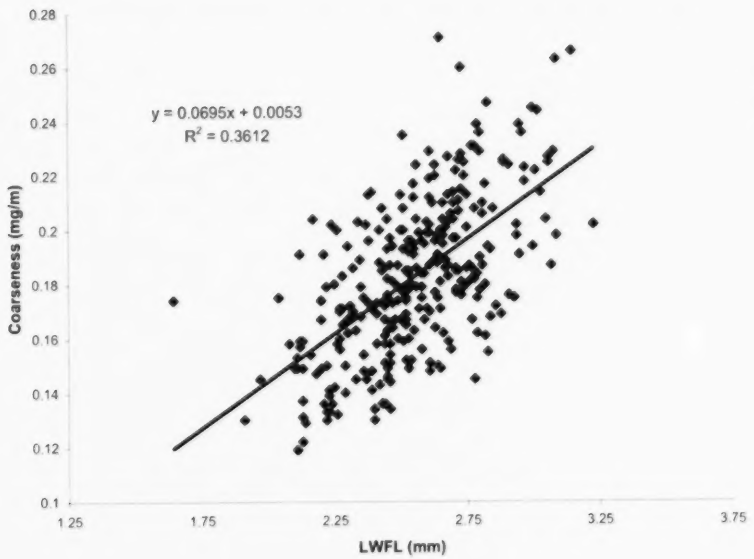

Figure 6. Coarseness versus LWFL for all sites with trend line and correlation value.

SilviScan

Figure 7 shows the result of SS3 density measurements (representing the 60- to 80-year age class) plotted against time since death for all sites. Density is expressed as basic density (oven-dry mass / green volume). This measure allows density comparisons independent of moisture content of the wood. These data show no trend when displayed as a function of time since death, therby indicating that wood density is not affected by beetle-induced mortality. Published values for wood density of lodgepole pine grown in British Columbia are between 324 kg/m^3 and 451 kg/m^3 (Gonzalez 1990) and the SS3 data fall within this range except for data from two sites (08-03 and 04-01), which show greater densities.

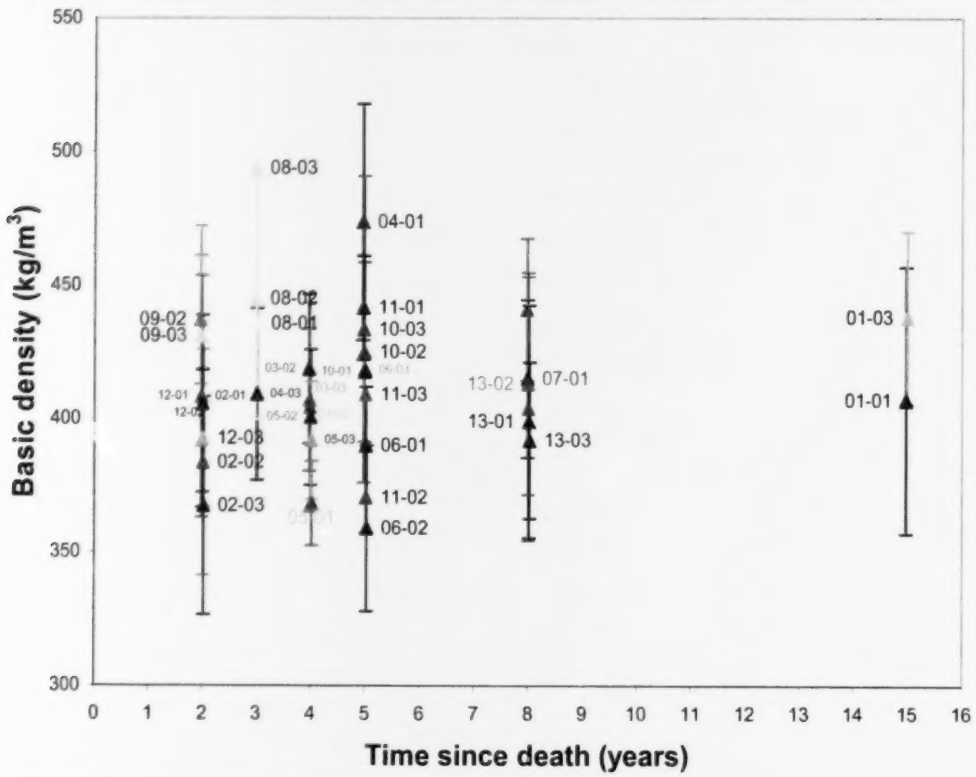

Figure 7. SilviScan 3 density values from the 60- to 80-year age class versus time since death for all sites. Error bars represent 1 standard deviation at 95% confidence interval. Large standard deviations are a function of the way that density is measured (50-micron intervals). This captures the variation between early- and late-wood portions of growth rings and varies from 200 kg/m^3 to 1000kg/m^3.

These data indicate that, within the sample area, density is stable across the range of time-since-death classes measured. If decay fungi were present, loss of wood mass would be expected to result in reduced basic density.

Because of the short interval (50 microns) between density measures acquired with SS3, density profiles can be created. These profiles show delineation between annual growth rings due to variation in early-wood and late-wood densities. Areas of high density show late-wood regions within a growth ring. These late-wood regions are then followed by a sharp drops in density correlating to the following season's early-wood growth patterns. Therefore, density profiles produced by SS3 provide annual ring profiles. (See Figure 8 for an example of these profiles.)

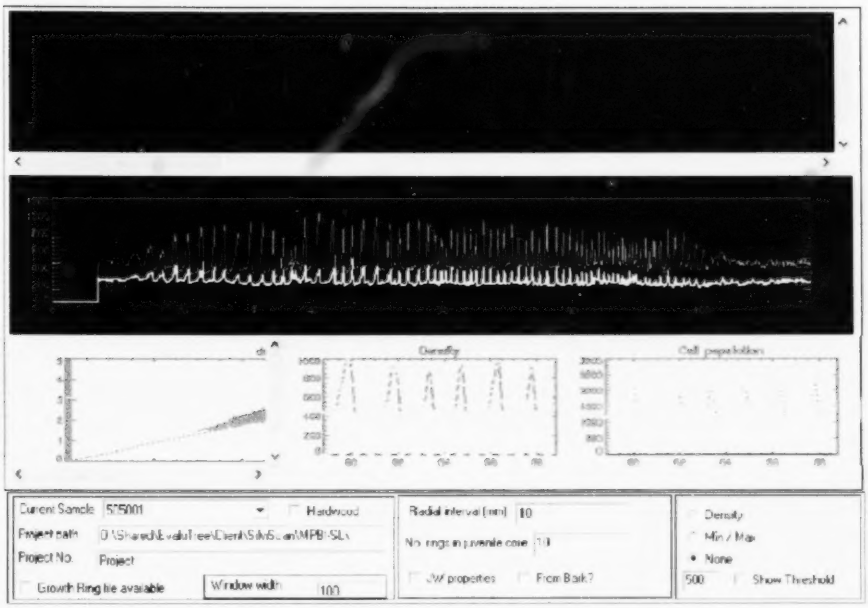

Figure 8. SilviScan 3 density profile for sample 505001 (Site 01-01, tree 1). Delineations between late wood and early wood define annual ring boundaries. A section of this profile is highlighted in the two windows to the right below the profile. These windows show density and cell population (which correlates to density) around the 54-mm section of the core.

The three layers of the secondary cell wall in softwood tracheids contain bundles of cellulose molecules known as microfibrils (Smook 1994). The helical angle of microfibrils in relation to the axis of the wood fibre is the microfibril angle (Lawrence and Woo 2005). The secondary wall makes up the bulk of the cell wall; therefore extreme variations in MFA across time-since-death classes may indicate breakdown in individual fibres and deterioration in shelf life.

Figure 9 displays MFA against time since death for all sites, and shows no such correlation.

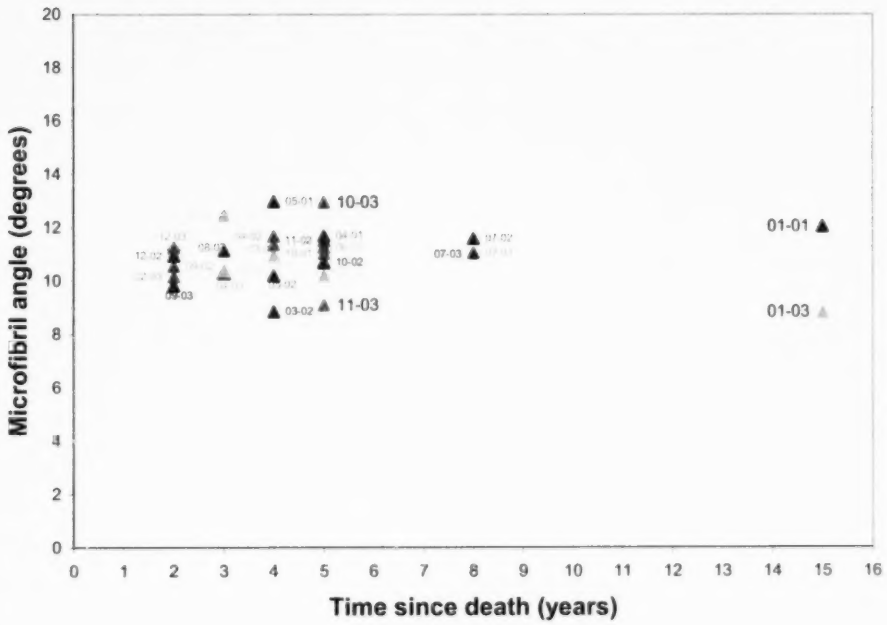

Figure 9. Microfibril angle versus time since death for all sites over the 60- to 80-year age class.

The data does not suggest any expected effect of beetle-induced tree mortality on MFA of individual tracheids. Many of the sites display clumping within each subzone (e.g. site 07-xx, site 12-xx and, to a lesser extent, site 08-xx and site 5-xx). This suggests there may be some correlation between biogeoclimatic subzone (regional macroclimate) and MFA. This would imply some environmental control on MFA, as discussed above with respect to LWFL. However, genetics may play a large part in MFA, as do site effects such as slope position and angle.

Modulus of elasticity (MOE) estimates stiffness of wood and is an important consideration for the solid-wood industry sector (Lawrence and Woo 2005). SilviScan 3 estimates MOE based on measures of density, MFA and information from X-ray diffraction patterns related to S1 and S3 layers, parenchyma and amorphous cellulose present in the cell wall (Lawrence and Woo 2005). Figure 10 illustrates the relationship between MOE and time since death for sample sites. A notable decrease in MOE plotted against time could indicate a weakening of the wood fibre. This weakening could indicate cell-wall deterioration.

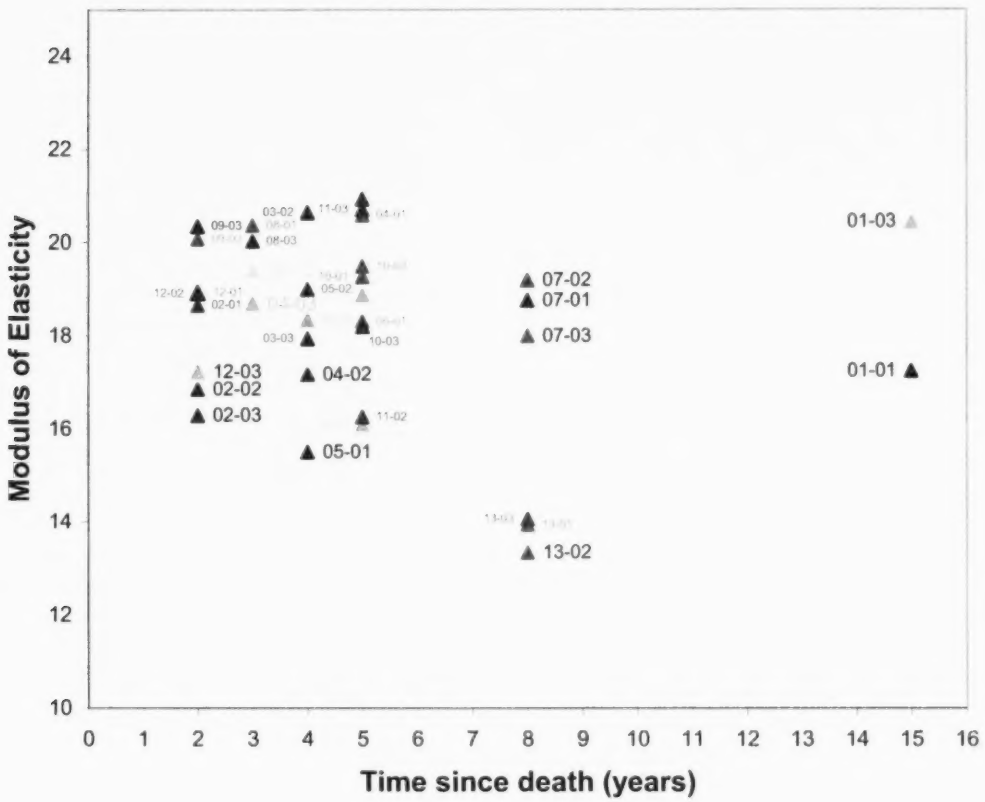

Figure 10. Modulus of elasticity from the 60- to 80-year age class versus time since death for all sites.

Modulus of elasticity shows no deterioration over the sample area and time-since-death measures, suggesting that wood stiffness (measured by MOE) will remain at pre-infestation uplift levels for the sites analyzed. Low MOE values for site 13 correlate with the high MFA values displayed in Figure 6. Generally a high MFA correlates with a low MOE (stiffness) value. Microfibril angle is more likely to produce the low MOE values shown here than is any tracheid deterioration due to beetle-induced mortality.

SilviScan 3 uses density and tracheid diameter to calculate cell-wall thickness. It is important to note that SS3 uses cell-wall density (as opposed to wood-density values as reported above) to calculate this property. SilviScan 3 uses a constant of 1500 kg/m^3 ± 50 kg/m^3 to calculate this value (Lawrence and Woo 2005). Figure 11 compares average wall-thickness values and their associated standard deviations for all sites.

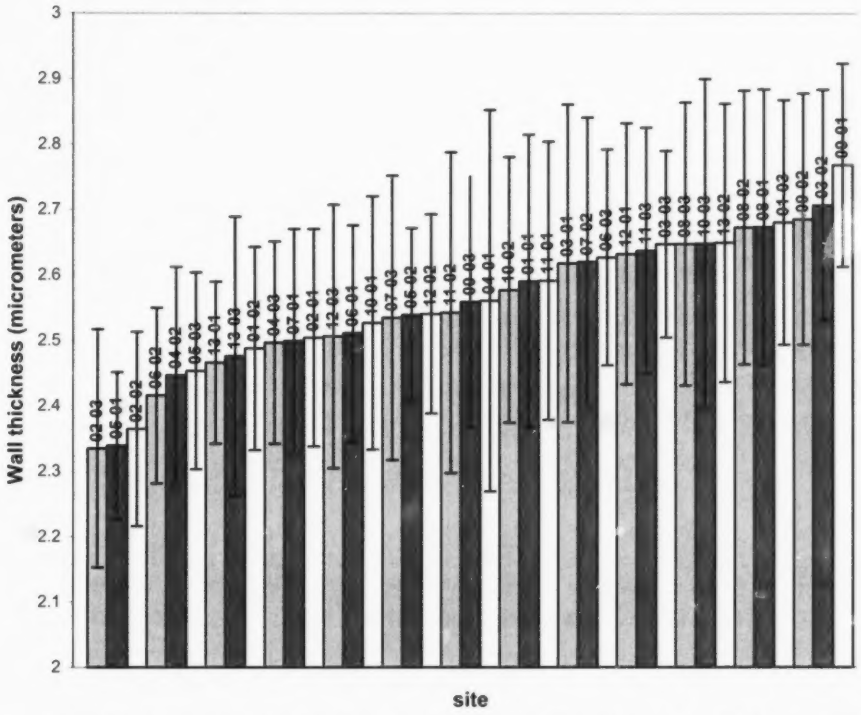

Figure 11. Histogram of average cell-wall thickness by site for the 60- to 80-year age class. Error bars represent 1 standard deviation.

Extractives

Surprisingly, no correlations between extractive content and time since death were observed across the sites sampled for this study (Figure 12 shows total extractive content against time since death). Previously, we had observed 50% to 100% increases in extractives content at the time of beetle attack (0 years, in Figure 12). Whereas highly volatile extractives may evaporate quickly after death and, therefore, would not change across time-since-death classes beyond that stage, changes in non-volatile extractives content would be expected with increased time since death. It is likely that other external factors affect removal of extractives from standing trees; for example, bark retention, rainfall, or heat.

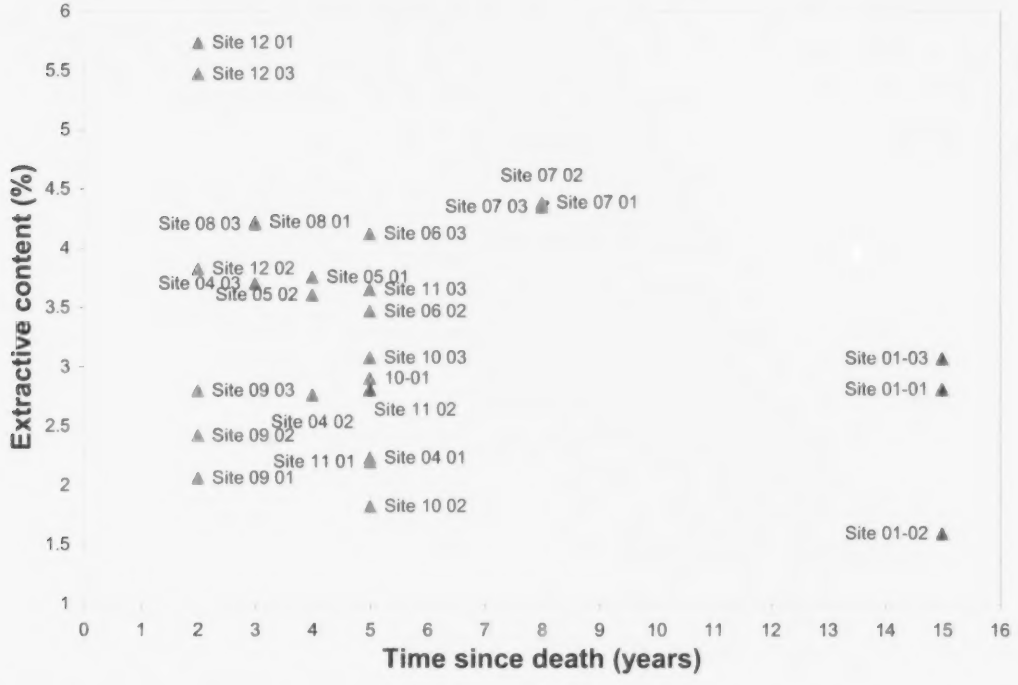

Figure 12. Extractive content versus time since death for all sites.

Extractive content in sound, live lodgepole pine varies from 1% to 2% in sapwood and from 2% to 4% in heartwood (Woo 2005). Sites 12-01 and 12-03 show values that are well above these norms; sites 08-03, 08-01, 07-01, 07-02 and 07-03 show values marginally above these norms. Sites 12-01 and 12-02 may be expressing high extractives content due to high pitch production during time of beetle attack. The trees were trying to pitch the beetle out and produced a greater amounts of extractives. Such elevated extractive contents during green and red attack have been reported, but in general are followed by a rapid decrease in extractives content, partly due to loss of volatiles. Also, the degree of elevated extractives production is tree dependent. These reasons may explain why not all sites show elevated extractive content in the early years after death.

Decay Extent Estimations and Moisture Content

Decay Extent

Decay (as measured by caustic solubility methods described above) is an important consideration in both the solid-wood and pulp and paper sectors of the forest industry. Decay of beetle-affected wood does not appear to be directly correlated to time since death, as can be seen in Figure 13.

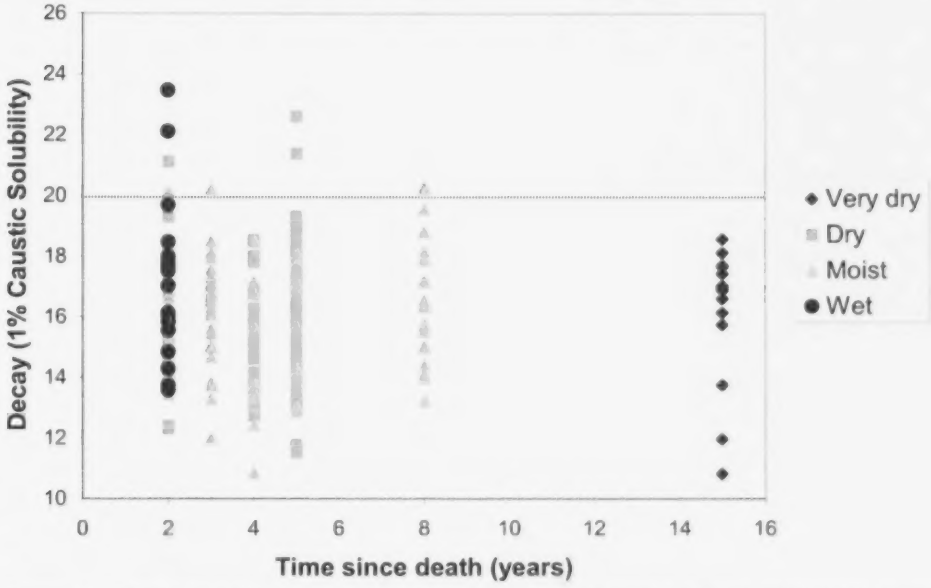

Figure 13. Caustic solubility versus time since death for a sub sample of sites, subdivided by moisture regime of the sample sites (very dry to wet). The dashed line represents the demarcation of sound (<20%, [1%] caustic solubility) to decayed (>20%, [1%] caustic solubility).

Caustic solubility is used as a measure of decay for wood. Values greater than 20% are regarded as decayed in lodgepole pine; many of the above samples are above that value. However, there is no correlation with time since death: decay appears to be independent of that variable.

Varying decay may be explained by the prevalence of tree diseases in British Columbia that frequently affect live and dead lodgepole pine trees. These diseases are widespread and can cause elevated measures of caustic solubility. Examples of these diseases are *Trichaptum abietnum* (Dickson : Fr.) Ryvarden (a sapwood rot) and *Fomitopsis pinicola* (Sw. : Fr.) Karst (a heartwood rot) (Allen et al. 1996). Decay fungi thrive in wet environments; it is expected that decay levels for wood from wet subzones will increase faster and more significantly with time since death, whereas decay levels for wood from dry subzones will be less affected.

Figure 13 shows that little decay of wood occurs in very dry subzones show even after 15 years since death, but that wood from wet subzones has slightly higher decay contents, on average, just after two years after death. This level can be expected to increase.

Although directly measured with caustic solubility, decay content can also be inferred from many of the attributes discussed above. For example, decay affects wood density, because tracheid material is lost to decay fungi, thereby leaving less dense material. By this same logic, coarseness values, cell-wall thickness and MOE should also be reduced in decayed wood. The relative consistency of these attributes across time-since-death classes confirms caustic solubility measures that indicate no significant decay for the sample area.

Moisture Content

Moisture content showed a negative correlation with time since death in this study (Figure 14). These findings support the findings of other studies (Lewis and Hartley 2005; Woo et al. 2005).

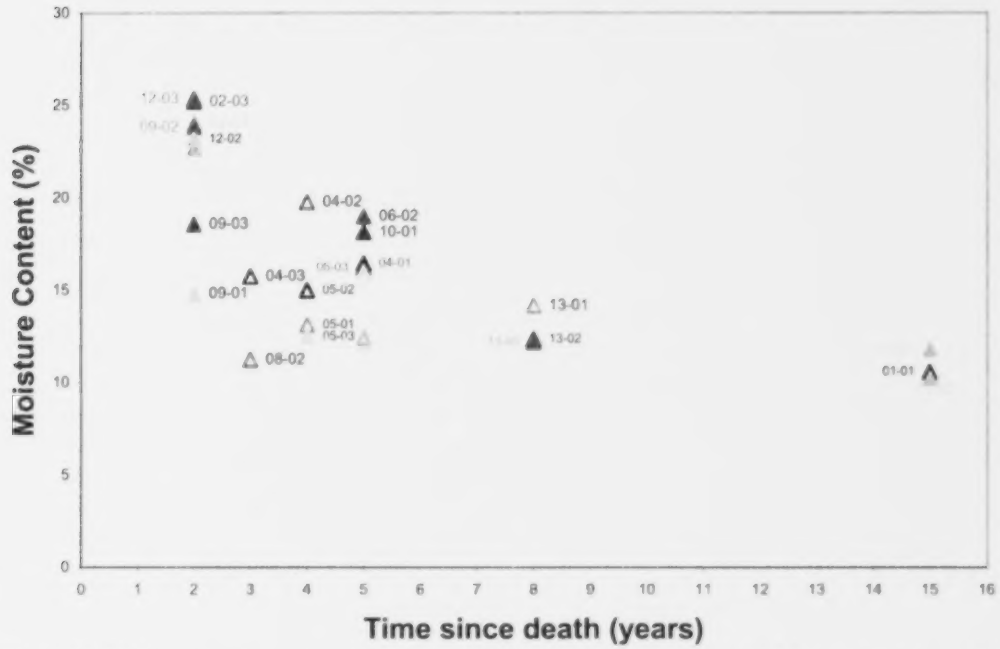

Figure 14. Moisture content versus time since death for all sites shows a trend of decreasing stem moisture with increasing time since attack.

Moisture content losses in standing dead beetle wood are related to checking (Lewis and Hartley 2005). Checking will likely be one of the key determinates in beetle-affected pine for the solid-wood sector. Lewis and Hartley (2005) note that checking is significant after moisture content of wood falls below the fibre-saturation point (generally regarded as 30% in lodgepole pine). These data indicate that checking will become an issue for beetle-affected wood within 2 years of tree death. It should also be noted that a hysteresis effect is seen when wood moisture drops below the fibre-saturation point; it is then not possible to fully rewet the wood, as shown by Woo (submitted as part of MPBI #8.50—unpublished data).

Mathematical relationships between moisture content and time since death are displayed in Figure 15. While trends are evident, stronger mathematical correlations between these two variables would be required to predict moisture content of a given stem by time-since-death characterization.

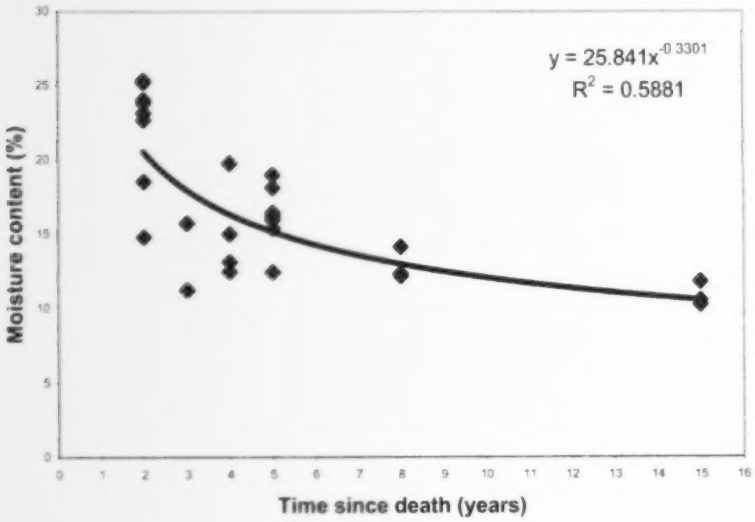

Figure 15. Moisture content versus time since death for all sites display a negative exponential trend line and a correlation value (R^2).

Sampling of multiple site series within a given subzone allows for comparisons of site characteristics that exclude climate as a variable. This allows analysis of site effects on wood characteristics: in this case, moisture content. Relative soil moisture regimes, which were deduced for each site, were compared against wood moisture content. Although these analyses showed no overall correlation, some sites showed trends consistent across different biogeoclimatic subzones. Figure 16 illustrates this relationship.

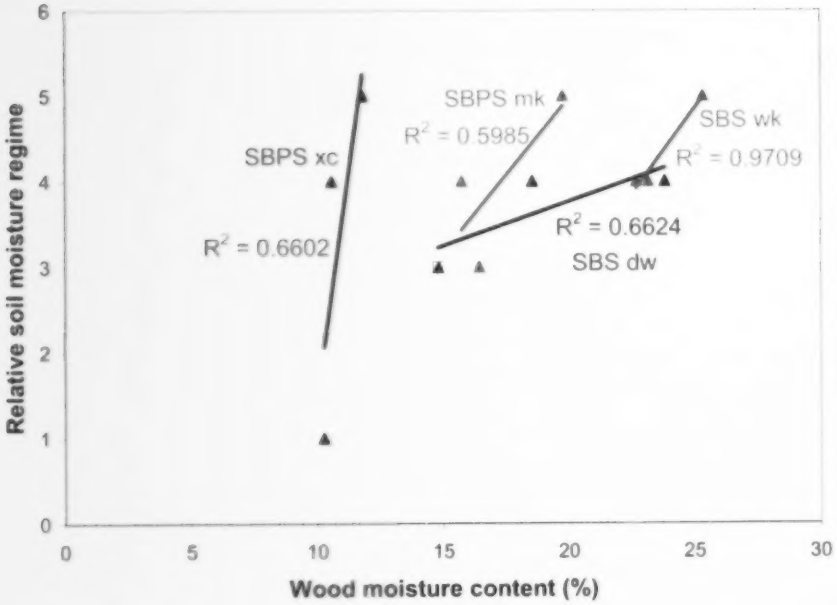

Figure 16. Selected sample sites showing possible site effects on wood moisture content. These trends are independent of climate as each series is within one subzone (representing the regional macroclimate) and kill date (all trees at one sample site are assumed to have the same kill date). This generally shows an increase in wood moisture content with an increase in relative soil-moisture regimes.

Figure 16 suggests soil moisture may influence wood moisture content in standing dead trees at some sites. Some wicking effect may be possible, but water is unlikely to wick as high as breast height (1.3 m) in dead trees; trees on wetter sites may have higher relative moisture contents near the base and in the roots. This factor could potentially be compounded by the lack of evapotranspiration—loss of water from the soil both by evaporation and by transpiration from plants—on sites where all the trees are dead. These wet sites may decay tree roots more quickly and make these trees more susceptible to windthrow. This would affect shelf life of trees at such sites. There is no empirical evidence associated with this study to support this hypothesis, however.

Relationships between wood moisture content and decay were explored. It was theorized that lack of decay evident in analyzed samples was a function of low moisture content discussed above. Profiles from 47 cores for both moisture and decay were plotted against each other to determine if these relationships existed (Figure 17). Figure 17 shows that decay and moisture are not related in this study.

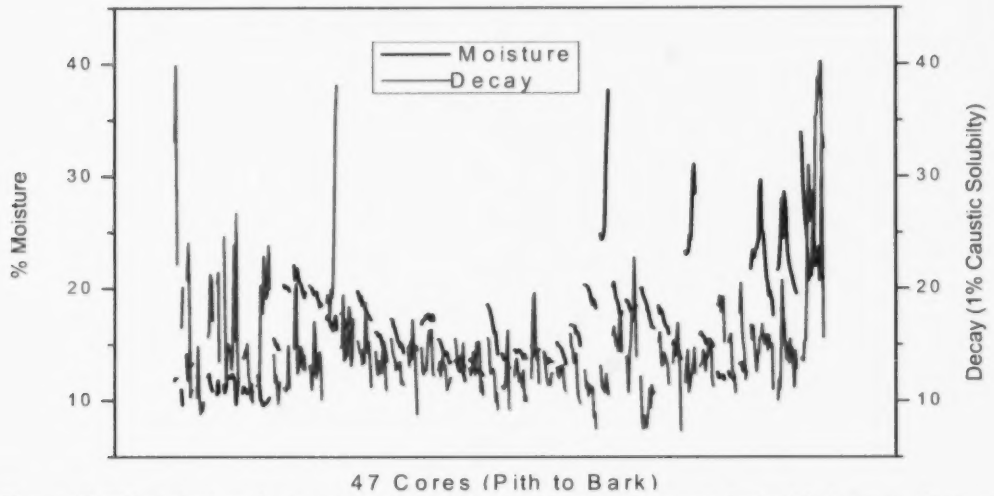

Figure 17. Pith-to-bark moisture and decay profiles for 47 cores show no relationship between those two variables.

Quantification of checking by image analysis of disks

A method has been developed to rapidly quantify the extent of checking in wood discs. A summary of the results is shown in Table 5.

Table 5. Summary of results of disc image analysis

Disc sample	No. of checks	Disc radius† (mm)	Avg. check length (mm)	Avg. check length as % of disc radius	Ratio of total check length to disc radius
T4	4	188	103	55	2.2
T5	3	151	55	36	1.1
T6	14	158	50	31	4.4
T7	5	191	49	26	1.3
T8	4	151	31	21	0.8
T9	6*	189	85	45	2.7

* T9: Image analysis identified nine discrete check segments in this disc: four were aligned along the same general radial path, thus were considered to constitute a single check for the purposes of calculating check dimensions.

† Disc radius was derived using Image Pro, which finds the average diameter based on diameter measurements through the centroid at 2° intervals around the disc.

In Figure 18, data for each disc is shown superimposed on a processed image of that disc. This combines the qualitative and quantitative information for each sample.

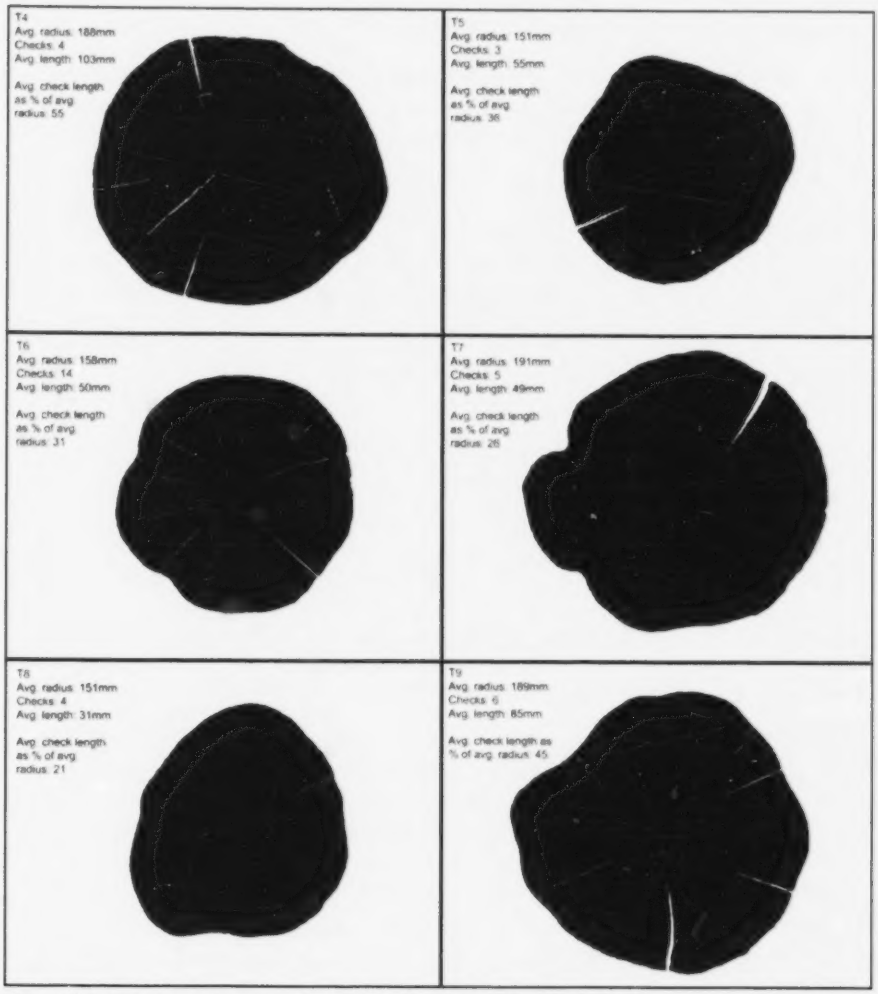

Figure 18. Processed images of six disc samples, with selected image-analysis results superimposed

Conclusions

A preliminary assessment of wood quality associated with site and time since death for mountain pine beetle-killed wood has been completed for 39 sites. Of the variables measured, moisture content was the only one that showed a significant trend when compared with time since death. These findings are supported by a synthesis of literature and experiential knowledge on beetle-killed lodgepole pine-tree deterioration (Lewis and Hartley 2005).

The loss of moisture may be a greater concern to the solid-wood industry sector, as it is closely related to checking in wood, which can adversely affect product quality (Lewis and Hartley 2005). Dry-wood problems are not exclusive to the solid-wood sector, however, and pulp and paper operations will be forced to address these issues. This appears to be the largest challenge affecting pulp and paper producers faced with using increasing amounts of beetle-killed pine.

Wood and fibre properties fundamental to both solid lumber and pulp and paper production (including length weighted fibre length, coarseness, wood density, microfibril angle, wood stiffness and decay) do not appear to be affected by beetle-induced tree death up to 5 years after mortality for sites surveyed. These fundamental wood and fibre properties appear to remain stable over the time frame examined in this study.

Over the longer term, as the solid-wood sector experiences an inevitable reduction from current harvest levels, the pulp and paper sector (reliant on residual chips from such operations) will have less amounts of fibre available for processing. This paper demonstrates the usability of advanced grey-stage wood in pulp and paper operations.

Recommendations

This study suggests that standing dead lodgepole pine trees killed by mountain pine beetle do not deteriorate in expected ways. In reference to the pine beetle outbreak on the Chilcotin Plateau, Lewis and Hartley (2005) note that "decay of beetle-killed pine was not a factor in use of the wood until the trees fell over, then decay progressed rapidly". However, some additional sampling is recommended, as sampling for this study disproportionably favoured sample sites with times since death of 2 to 5 years, and data analysis was further hindered by the uncertainties in kill-date estimates.

As external factors do not appear to be a reliable indicator of end-use applicability, emphasis needs to be placed on internal wood-quality deterioration. While the limited sampling in this study did not conclusively result in predictions of wood deterioration with time since death, industrial experience indicates that such relationships must exist. Future work will be greatly aided by the findings of this study. In particular, work can be more rapidly completed using the databases of this work as a basis for near-infrared analysis and correlation of samples thereby reducing project costs. Selected analyses by methods employed in this study should be undertaken for validation purposes.

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